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HIGH-SPEED TRANSMISSION SYSTEM FOR OPTICAL CHANNELS

CROSS-REFERENCE TO RELATED APPLICATIONS

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This Application claims priority from Provisional Application 60/177,034 entitled HIGH SPEED TRANSMISSION FOR OPTICAL CHANNELS filed on 1/17/00, which is incorporated by reference herein as though set forth in full.

FIELD OF THE INVENTION

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The present invention relates generally to apparatus and methods for high speed data transmission over optical channels, and, in particular embodiments, to transmission of data using pulse amplitude modulation, trellis coding, and equalization techniques.

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BACKGROUND OF THE INVENTION

The demand for higher capacity data transmission systems continues to increase. To satisfy the ever increasing demand for more data transmission capacity higher baud rate systems such as optical channels have been used. At high baud rates some optical fibers may exhibit phenomena such as multimode transmission

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characteristics and intersymbol interference, which can limit the signaling rate available on that fiber. Therefore, there is a need within the art for methods and apparatus that are capable of higher baud rates, and for those which can compensate for the problems encountered with high speed data transmission.

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SUMMARY OF~~THE INVENTION~~ Embodiments of the invention

In one aspect of the invention, an apparatus for transmitting data on a fiber optic channel is disclosed. The apparatus comprises a trellis encoder that accepts data to be transmitted, applies a convolutional coding to a portion of the data, and produces a trellis coding of the data to be transmitted. A subset mapper accepts the trellis coding

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and produces a plurality of pulse amplitude modulated (PAM) symbols from the trellis coding. A Tomlinson precoder accepts the PAM symbols and applies a Tomlinson precoding the PAM symbols. A converter converts the PAM symbols into a form for coupling into a fiber channel.

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BRIEF DESCRIPTION OF THE DRAWINGS

These and other features, aspects, and advantages of the present invention will

5 become better understood with regard to the following description, appended claims, and accompanying drawings where:

Figure 1 is a block diagram illustrating components of an optical data communication system.

Figure 2 is a block diagram of a optical communication system according to an embodiment of the invention.

10 Figure 3 is a block diagram illustrating a fiber optic transmitter according to an embodiment of the invention.

Figure 4 is a graphical illustration of Tomlinson-Harashima precoding (THP).

Figure 4a is a graphical illustration of the mapping of excess pulse amplitude modulation levels which are produced by a Tomlinson-Harashima precoder.

15 Figure 5 is a block diagram of a receiver, according to an embodiment of the invention.

Figure 6 is a simplified block diagram of a receiver, which contains a decision feedback equalizer (DFE).

Figure 7 is a graphical illustration of the impulse response of an exemplary fiber

20 channel.

Figure 8 is a block diagram illustrating a fiber channel model used in conjunction with a laser model based on the rate equations.

Figure 9 is a graph representing of the impulse response of a linear system having a Gaussian impulse response.

25 Figure 10 is a graph illustrating an output of a laser model based on the rate equations.

Figure 11 is a graph illustrating an expanded portion of the graph illustrated in Figure 11.

Figure 12 is a graph of the simulated output of the laser model of Figure 10 after

30 passage through a simulated channel.

Figure 13 is an eye diagram of a simulated receiver equalizer, illustrating a transition between a bilevel training mode and receiving PAM-5 symbols.

Figure 14 is a graph of a magnified portion of the graph of Figure 13, illustrating

35 the convergence of the equalizer during a training sequence.

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DETAILED DESCRIPTION OF THE INVENTION

The demand for higher data carrying capacity transmissions systems continues to increase. Accordingly, embodiments of the present invention relate to methods and
5 apparatus for increasing the rate of data transmission in optical transmission systems.

Figure 1 is a block diagram illustrating a prior art optical data communication system.

In Figure 1 a data source 101 provides data to be transmitted over fiberoptic channel 109. Data source 101 may be, for example, the Internet, a cable television
10 head end, a corporate network or a variety of other data sources.

Data from data source 101 is provided to an encoder 103, which encodes the data. Encoding may encompass representing the input data from the data source 101 in a variety of ways. In the exemplary system of Figure 1 the data encoding comprises translating the data received onto a series of OOK (On Off Keying) symbols for
15 transmission using a laser. OOK represents the data as a series of on-off pulses or two levels of optical intensity.

Once the data is encoded, the encoded signal is coupled into an optical channel driver, such as a laser driver 105, which controls the intensity of a laser 107. The output of laser 107 is coupled into a fiber optic channel 109. The fiber optic channel is
20 further coupled to an optical receiver 111. The optical channel 109 may be of various lengths depending upon the application.

The optical receiver 111 accepts the signal provided by the fiber optic channel 109 and converts it into an electrical signal. The electrical signal, representing the transmitted data, is provided to an OOK data decoder 113. The data decoder 113
25 reverses the process of the encoder 103 and recreates the data provided by the data source 101. The data from the decoder may be then routed, for example using a data router 115, to various user devices. An exemplary user device 117 then receives data, such as video data, from the data router 115.

Figure 2 is a block diagram of an optical communication system according to an
30 embodiment of the invention. Transmitter 200 communicates with receiver 222 over channel 213. In Figure 2 the data to be encoded is coupled into a trellis encoder 201. The trellis encoder 201 includes convolutional coder 206 and subset mapper 203. The trellis encoder 201 may be a single trellis encoder or it may be a series of trellis encoders in parallel.

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The outputs of the convolutional coders 206 are further coupled into subset mappers 203. A subset mapper accepts the convolutionally encoded signal and produces multilevel symbols 205 as an output. The multilevel symbols are then coupled

5   into equalizers 207. The equalizers 207 are used to compensate for the non-flat response of a channel 203. After equalizing the multilevel symbols, the equalizers provide the resultant symbols to one or more digital to analog converters (D/A) 209. The digital to analog converters 209 accept the equalized multilevel symbols, and convert them into analog signals. The analog signals are then coupled serially into an

10   optical source such as a laser 211. The digital to analog (D/A) converter(s) provide successive signals to laser 211 during a second time period, and so forth. In other words a signal from a first D/A converter may be provided to the laser 211 during a first time period, then a signal from a second D/A converter may next be provided to the laser 211. In such a manner multiple symbols from multiple data sources may be

15   transmitted by the single laser 211. Alternatively, a single D/A converter may accept successive values from multiple data sources, converting them into a series of analog values to be used to modulate the intensity of the laser output 211.

The output of the laser 211, modulated by the analog representation of the multilevel symbols, is coupled into the optical channel 213. The optical channel 213

20   transmits the intensity modulated laser signal to an optical-to-electrical converter 215. The optical-to-electrical converter 215 accepts the optical signal from the channel 213 and converts it back to an intensity modulated series of electrical signals. The optical-to-electrical converter 215 then provides the amplitude-modulated signals to one or more analog-to-digital (A/D) converters 217. The A/D converters converts the series

25   of analog signals to digital signals. The digital signals are provided to one or more trellis decoders 219 where the trellis-encoded digital signals are decoded. The output of the trellis encoders are provided to a physical coding sublayer (PCS) unit 221. A physical coding sublayer (PCS) may provide bit manipulation, such as decoding, to the signals decoded by the trellis decoder 219. The data output of the PCS 221 is then provided

30   to a user interface such as an XGMII (extended Gigabit Media Independent Interface).

Illustratively, the optical communication system depicted in Figure 2 has particular characteristics. For example, the channel 215 is considered to be a standard 62.5/125 µm fiber. Fiber is commonly specified in terms of a bandwidth times length product. For a 62.5/125 µ meter fiber a typical bandwidth times length product is 500

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MHz/km. 500 meters of such fiber would typically yield a 1 gigahertz bandwidth for a laser wavelength of 1310 nanometers.

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To transmit a signal at or less than the Nyquist rate, the minimum bandwidth must equal one half of the symbol rate of the channel. The Nyquist bandwidth of a channel is the maximum rate at which signaling can occur on that channel without intersymbol interference (ISI). In other words, a system cannot transmit signals faster than the Nyquist rate without intersymbol interference. However, an equalizer such as 207 can be used to remove intersymbol interference. Equalization in Figure 2 is shown

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within the transmitter 200. Such equalization is called transmit side equalization. Equivalently, equalization may be applied at the receiver 223. For example, decision feedback equalization (DFE) may be used at the receiver 223. Although the equalization can be done equivalently on the transmitter as well as the receiver side, there are certain advantages to placing the equalizer in the transmit side. For example,

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if the equalization is placed within the receiving side, the trellis decoder and an equalizer must function concurrently. Concurrent trellis decoding and equalization is a complication within the receiver that can be avoided by having the equalization circuit in the transmitter. It is difficult to combine an equalizer and a trellis decoder, in a receiver, because such a receiver would have to decode the trellis while attempting to

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compensate for the intersymbol interference. If the equalization is done in the transmitter, there is no necessity to compensate for intersymbol interference while decoding the trellis coding.

Embodiments of the present invention may include, for example, a single trellis encoder, a single symbol mapper, a single equalizer etc. Alternatively, the same

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components may be replicated multiple times the signals time multiplexed from such parallel components in order to couple them in and out of a single fiber channel. To simplify the disclosure, however, the components will be illustrated as single components. Those skilled in the art will realize that the same components may be used in a variety of parallel configurations.

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For the purposes of example, the multilevel symbols 205 are considered to be part of a PAM-5 (pulse amplitude modulation - 5 level) alphabet.

Figure 3 is a block diagram illustrating the fiber optic transmitter 200 according to an embodiment of the current invention. Detail of the transmitter 200 is illustrated in Figure 3. The trellis encoder 323 accepts a group of R bits from the data source 202.

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The trellis encoder 305 is a rate M/(M+1) convolutional coder of the R bits which are

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input to the rate m/(MH) encoder. R-M bits will be unencoded and M bits will be encoded. The output of the convolutional coder 305 comprises (M+1) bits. The R-M unencoded bits and the M + 1 coded bits, which are output from the convolutional coder

5   305 are provided to a subset mapper 307. The subset mapper 307 maps the received bits into a series of multilevel symbols 309, for example, PAM 5. The combination of convolutional coder 305 and the R-M unencoded bits comprises a trellis encoder 323. The pulse amplitude modulated signals A_1 through A_N have 5 levels, but may have any number of amplitude levels, depending on the pulse amplitude modulation scheme

10 chosen.

The fiber optic channel, as discussed above, illustratively exhibits multimode transmission characteristics at any Nyquist bandwidth of 1 GHZ. Accordingly, the bandwidth available in the channel is smaller than required to signal without intersymbol interference (ISI) at a 10 GHZ rate. To achieve the 10 GHZ signaling rate, the channel

15 operates in the presence of intersymbol interference. One way to compensate for intersymbol interference is to use an equalizer in the receiver. For example, a decision feedback equalizer (DFE) may be used. The DFE is discussed in the receiver section.

A further way to compensate for the effect of intersymbol interference is to use a Tomlinson precoder 311.

20 In Figure 3 multilevel symbols 309 are provided to a Tomlinson Precoder, for example in a 10 gigabit per second (GPS) transmission system implemented using a five level pulse amplitude modulation - 5 level (PAM-5) transmission scheme. The baud rate necessary to achieve a 10 GPS transmission is reduced to five gigabaud because each PAM-5 symbol can represent five different values.

25 There are multiple advantages to reducing the baud rate by using pulse amplitude modulation. One advantage is that the system can operate over multimode and limited bandwidth channels over greater distances than would be possible if on/off keying (OOK) were used. Another advantage, of using PAM instead of OOK, is that the PAM symbols can represent multiple bits of information. Accordingly, the speed of the

30 electronic circuits needed to create the transmitted signal at the transmitter is reduced. Consequently, the speed of the electric circuits needed at the receiver is also reduced. By reducing the required speed of the electronic circuits, technology such as CMOS (complimentary metal oxide semiconductor) may be used to implement the electronic circuitry. In contrast, high speed electronic circuits can often require expensive high

35 speed technology such as gallium arsenide or indium phosphide. Because of the

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higher levels of integration presently available using CMOS, a greater level of integration is possible than with such technologies as gallium arsenide or indium phosphide, and so it is advantageous to use PAM symbols to decrease the signaling rate while keeping the baud rate constant.

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A potential disadvantage of using multilevel encoding such as PAM-5, instead of the more traditional on/off keying, is that a higher signal to noise ratio (SNR) may be required of the channel since OOK needs to represent only two levels whereas PAM symbols are multiple levels. By using multiple levels the distance between levels is reduced, over using two levels. Because the distance between levels is reduced the available noise margin is also reduced. To reduce the required signal to noise ratio to a level equivalent to the OOK system, PAM-5 modulation may be combined with trellis coding as illustrated in the embodiment of the invention illustrated in Figure 3.

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In Figure 3 a Tomlinson Harashima (Tomlinson) precoder 311 functions as a transmit side equalizer. A traditional equalizer in a receiver compensates for distortion and uneven frequency response caused by the transmission channel. Including the fiber on laser equalization, however, can be done equivalently in a receiver or a transmitter. In either case the result is a signal characteristic that, when combined with the channel characteristic, ideally results in a flat overall response.

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A problem with attempting to equalize a fiber channel is that the fiber may exhibit nulls. In other words, the fiber channel transfer function permits very little signal transmission at a particular frequency. An equalizer, attempting to compensate for such nulls, may require an high gain to make up for the poor response of the channel. High gain may produce an unstable response in the equalizer.

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Tomlinson Harashima precoding may be used to compensate for frequency nulls within the channel. The output of the Tomlinson precoder 311 is provided to a Digital Analog (D/A) converter 313. The D/A converter produces an analog signal, which is used to modulate the intensity of the laser 211. The Tomlinson precoder is shown as a simplified representation in 311. The Tomlinson precoder 311 may actually be a group of Tomlinson precoders, each of which operates on one PAM-5 symbol. The PAM-5 symbols thus generated are multiplexed into the D/A converter 313.

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Figure 4 is a graphical illustration of Tomlinson-Harashima precoding (THP). In Figure 4, Channel 411A, which is identical to Channel 411B, can be described by a Z transform. The characteristics of Channel 411A and 411B can be described by the expression "1+D(Z)." The term "D(Z)" term is responsible for the intersymbol

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interference exhibited by the channel. If it is desired to compensate for the characteristic of the channel within the transmitter, a filter with a transfer characteristic inverse of the channel must be added. By implementing a feedback loop comprising the summation unit 405A and the feedback filter 407A, a transfer characteristic of $1/(1+D(Z))$ is created. The total response would then be $1/(1+D(Z))$ times $1+D(Z)$ resulting in a net channel characteristic of one, which is the combined response of the precoder and the channel. The combined response of the precoder and the channel is therefore a flat response which does not introduce any dispersion, and therefore, the signal at the receiver 413A is equalized.

Difficulties can be encountered because at frequencies where the channel has a lot of attenuation, the precoder will have a lot of gain to compensate for the attenuation. At such frequencies, the precoder may become unstable. Therefore, in order to stabilize the precoder and to limit the amplitude of the signal out of the precoder, a signal V_n represented by arrow 403 is added to the summation unit 405A. $V_n = K_n \times M$ where M is the number of levels being transmitted on the channel. In the present embodiment, which uses PAM-5, M has a value of 5. M is essentially the maximum number of levels desired at the output. Once the output signal of the precoder, V_n is computed, if the signal exceeds certain limits then V_n is subtracted from the signal Y_n and K_n is the smallest integer that brings the output Y_n back into the desired range. There is always a value for K_n that will meet this condition. M is essentially the maximum allowable range of the output of the precoder. Depending on the value of Y_n there is a unique integer value K_n that will bring the output of the precoder back within the range M. This is the basis of Tomlinson Harashima Precoding (THP). In other words, the THP does the inverse channel characteristic filtering then modifies the input to the summation unit by adding an integral multiple of M which at the output is bounded. The signal V_n is added to the input. The output of the channel sees a quantity equal to X_n plus V_n. In other words, the number of levels appearing at the receiver has been expanded. Therefore, the slicer in the receiver must be able to distinguish $X_n + V_n$ levels instead of just being able to distinguish X_n levels. One price for doing this type of equalization is the increase of the number of levels in the constellation at the receiver. Therefore, all that needs to be done in the receiver to recover the original PAM-5 levels is to implement a wrap-around scheme such that the excess levels are wrapped around into the original PAM-5 levels. The wrap around is illustrated in Figure 4A.

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Figure 4A is a graphical illustration of the mapping of excess pulse amplitude modulation levels produced by a THP, such as illustrated in Figure 4. In Figure 4A, 9 PAM constellation levels are present. The correct PAM-5 levels, that is 435, 437, 439,

5   441 and 443 are present. In addition, levels 431 and 433 which are higher than the highest PAM level 445, are present. Additionally, levels 445 and 447 are present which are lower than the lowest level 443 are present. In order to map the 9 levels back into the original 5 levels, a modulo type add or subtract is done. In other words, if the level out to be remapped are above the maximum levels, a modulo 5 value is subtracted.

10   In the present case, 5 levels are subtracted from level 433, and accordingly level 433 maps into level 443. Similarly, 5 levels are subtracted from level 431 and level 431 maps into level 441. Similarly level 445, which is below the lowest level of 443, has 5 levels added to it and level 445 is thereby mapped into level 435. Similarly, level 447, which is below the lowest level of 443, has 5 levels added to it and is thereby remapped

15   into level 437. If for example 6 levels were present above level 435 then 10 would be subtracted from the 6th level and the 6th level above 435 would map into level 443.

Referring to Figure 4 precoder 400B illustrates an alternate method of adding the correction factor V_n to the precoder. In precoder 400A signal Y_n is examined and then a value for K_n is decided on and the value V_n is then added or subtracted in the

20   summation unit 405A. In reality the operation of creating the adjustment value V_n is nothing more than a wrap around operation. The operation is comparable to the overflow in an accumulator. Therefore, in the precoder represented in 400B modulo block 417 is added. In the modulo M block 417, a wrap around operation is added to the precoder circuit and automatically accomplishes the adjustment accomplished by

25   the summation fo the V_n signal in summation block 405A in precoder 400A.

One problem with Tomlinson precoding is that the number of levels in the receiver may grow depending on the channel characteristics. For example, in a PAM-5 system the number of levels may grow to 15, 20 or more. The proliferation of levels in

30   the receiver may be a problem because within the receiver is an A/D converter sampling the multiple received levels. In order to accommodate multiple levels, the resolution of the A/D converter can be adversely impacted because the levels must be scaled so that they fit within the range of the A/D. That is, the resolution of an A/D converter discriminating between 5 levels is much better than the resolution of that same A/D

35   converter discriminating 15 levels. Therefore, adding levels can require a better A/D

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converter, that is one having more bits of resolution. It is therefore desirable to limit the number of levels presented to the receiver. The number of levels that are presented to the receiver can be accomplished by limiting the value of K_n in precoder 400A. Such

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limiting may lead to certain points falling outside of the allowed levels, however in return for the points falling outside of the allowed levels, the number of levels presented to the receiver can be limited. This form of THP is referred to as Dynamics Limited Precoding (DLP).

Precoding has several advantages over receiver side equalization. One

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advantage is that a precoder lends itself to a better parallel implementation than receive side equalization such as Decision Feedback Equalization (DFE). Another advantage of receiver side equalization is that when using trellis-coded modulation, precoding allows the trellis decoder to be substantially simplified, since the decoder then does not have to deal with intersymbol interference. The combination of precoding with trellis

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coded modulation can approach the Shannon bound for channel capacity when good modulation codes are used. Therefore, the present architecture can provide a close to optimal architecture.

Figure 5 is a block diagram of a receiver, according to an embodiment of the invention, illustrating the decoding of multiple signals transmitted across the same

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channel. In Figure 5, a photo detector 501 accepts a pulse amplitude modulated signal from the fiber optic channel 109. The photo detector 501 then provides a voltage signal, representative of the signal received from the fiber optic channel 109, to a pre-amplifier 503. The pre-amplifier 503 amplifies the signal provided by the photo detector 501 to a suitable level. Pre-amplifier 503 then provides the amplified signal to a high

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pass filter 505.

High pass filter 505 functions to prevent a phenomenon known as baseline wander. High pass filtering the input signal blocks low frequencies thus minimizing low frequency excursions. Photo detector 501, pre-amplifier 503 and high pass filter 505 generally define the optical receiver 111. The boundaries, however, between the

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optical receiver and decoder are somewhat arbitrary and other sources may define boundary line between these blocks differently.

The output of high pass filter 505 is provided to a programmable gain amplifier (PGA) 507. The gain of the PGA 507 is controlled by an automatic gain control (AGC) circuit 508. AGC circuit 508 controls the gain of the amplifier 507 according to signal

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levels at the output of the retiming block 511. The signal at the output of the PGA 507

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comprises a series of high speed pulse amplitude modulated voltage signals. The output of the programmable gain amplifier 507 is coupled into a plurality of interleaved analog to digital converters 509.

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The analog to digital converters (A/D) 509 are timed by a clock provided by the timing recovery circuit 515. Each A/D converter, however, receives its own phase of the clock in order to sample successive values using successive A/D converters. Because the values received by the A/D converters are sampled using a clock having different phases, retiming of the signals is necessary in order to create a synchronized parallel value. The retiming of the A/D samples takes place in retiming block 511. Retiming

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block 511 essentially comprises a clocked register circuit or equivalent. By interleaving N A/D converters in the analog to digital block 509, the clock rate of each individual converter can be reduced by a factor of N (over the use of a single converter). Without the interleaving of analog to digital converters 509 it may be difficult or impossible to

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fabricate an analog to digital converter, which could sample the input at a high enough rate, in order not to lose any successive values in the input data stream. By interleaving the A/D converters the necessity of using very high speed circuit technologies, such as gallium arsenide or indium phosphide may be avoided.

Parallel values from the retiming block 511 are provided to a fine AGC module

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513. The digital values of the synchronized parallel data can be examined in the fine AGC modules to determine whether the amplitude of the input signal is correct and to provide fine adjustments to the signal values. The timing recovery block 515 may adjust the timing of the analog to digital converters.

The output of the fine AGC block 513 is coupled into an N-dimensional trellis

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decoder 519. An N-dimensional trellis decoder includes N trellis decoders. The number of trellis decoders will vary depending on a variety of implementation details. The N-dimensional trellis decoder 519 decodes the symbols accepted from the fine AGC module 513 and converts them into digital data values.

Once the PAM-5 symbols have been decoded into bit patterns, they are provided

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to a physical coding sublayer (PCS) 521. The physical coding sublayer 521 provides bit manipulation, such as signal descrambling, etc. The physical coding sublayer 521 then provides a resultant bit stream to a system interface 523.

Figure 6 is a simplified block diagram of a receiver such as that illustrated in Figure 5 illustrating the addition of a DFE. The DFE in the receiver may be used

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instead of a Tomlinson precoder in the transmitter. Because equalization can be done equivalently in the receiver or transmitter the net equalization effect is the same.

5 The block diagram of Figure 6 does not illustrate the parallelism of the receiver illustrated by Figure 5. Figure 6, however does provide detail on the addition of equalization, which may be included in the receiver. A photonic signal is accepted by the detector 601. The detector 601 converts the received signal into a voltage and then provides the voltage signal to pre-amplifier 603. Pre-amplifier 603 amplifies the signal and provides it to high pass filter 605. A programmable gain amplifier 607 accepts the signal from the high pass filter 605 and provides it to an A/D converter 609.

10 The A/D converter 609 converts the analog signal from the high pass filter into a digital equivalent. An AGC block 608 accepts the digital value from the A/D converter 609 and controls the gain of the programmable gain amplifier (PGA) 607. The output of the analog to digital converter 609 is also provided to a fine AGC 613, where small adjustments in the signal are made. The output of the fine AGC 613 is then provided to a decision feedback equalizer 625. In order to explain the operation of a decision feedback equalizer reference will be made to Figure 7.

15 Figure 7 is a graphical illustration of the impulse response of an exemplary fiber channel. In Figure 7, point 719 represents a decision point where the value of the waveform 729 is sampled. Since the input waveform is an impulse, by definition only one value (represented by point 719) is provided to the channel. Therefore any subsequent response such as values 721, 723, 725 or 727 do not represent valid values which have been provided to the channel. Values 721, 723, 725 and 727 instead represent intersymbol interference caused by the impulse function. Samples 721, 723, 725 and 727 may be caused by the dispersion of the impulse waveform within a multimode fiber and are an undesirable feature of the fiber channel. They are generally caused by the differing propagation times of the impulse through different modes of the fiber. An equalizer, such as the illustrated DFE 625 may compensate for the distortion introduced by samples such as 721, 723, 725 and 727. The decision feedback equalizer uses an adaptive transversal filter 711 to generate a waveform equivalent to the trailing edge 731 of the impulse response. The trailing edge, represented by 731, is the portion of the waveform immediately after the sampled point 719 which includes spurious response points 721, 723, 725 and 727. The portion of the waveform 719 represents the spurious response of the channel. The adaptive transversal filter 623 makes a copy of the spurious response and subtracts it from the

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overall channel response in summation unit 619. The adaptive transversal filter is termed adaptive because it must adapt itself to the characteristics of the channel. In other words, the adaptive transversal filter must be trained using the channel

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characteristics in order to derive the proper response that will be provided to the summation unit 619. Once the slicer 621 detects which symbol is present, the adaptive transversal filter can then provide the response necessary to cancel the intersymbol interference present that would accompany the transmitted point.

The received waveform at a point prior to the summation unit 619 is shown on
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oscilloscope 615 as display 615A. Display 615A is a scatter type waveform that does not exhibit distinct levels. The waveform 631 may be generated by the adaptive transversal filter 611, in order to cancel the intersymbol interference (ISI) within the channel.

Once the intersymbol interference is subtracted from the incoming signal in
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summation unit 619, the output of the summation unit appears as shown on oscilloscope 617, in display 617A. Display 617A represents an eye diagram having five discrete levels. Once the levels have been well defined, as seen on display 617A, the slicer 621 is able to distinguish relatively easily between the symbols. The adaptive transversal filter 623 will respond to whatever symbol is found by the slicer 623 and
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provide the necessary waveform to cancel the intersymbol interference caused by the found symbol's transmission. The transversal filter generating an intersymbol interference replica, which must be subtracted from the incoming signal. The intersymbol interference waveform changes, depending on which symbol has been found by the slicer. The output of the decision feedback equalizer depends on the
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previously decoded symbols. The PAM-5 symbols found are then decoded by the Physical Coding Sublayer (PCS) 521 and then provided to an interface such as a XGMII interface (not shown).

To further set forth the inventive concepts, a preliminary simulation study of a PAM-5 system is discussed. To simulate the PAM-5 system a laser model was created
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using rate equations. Pseudo-random PAM-5 data was introduced to the laser model. The output from the laser model was provided to fiber model. The fiber modeled was a multimode type fiber modeled as a linear system with Gaussian Impulse Response. In one example a 62.5/125 µm fiber having a bandwidth of 1 GHZ conveys a loss nanometer signal.

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        The Nyquist theorem establishes that the bandwidth needed to transmit data at
a rate $F_b = 1/T$, without intersymbol interference, must be larger than or equal to ½ T.
Many communication systems however, signal at rates faster than 0.5 F_b, using special

5   techniques to control the intersymbol interference. Such techniques have been used
in the 100Base-TX and 1000Base-T Ethernet transceivers. The present model
examines signaling at 5 GBaud over multimode fibers with 1 GHZ bandwidth. The
present simulations contemplate signaling at 2.5 times the Nyquist rate (data rate
equals 10 Gb/s, baud rate F_b = 5 GHZ, bandwidth equals 1 GHZ). This bandwidth

10 assumption is consistent with 500 meters of 160/500 MHz-KM fiber at 1350 nanometers
(nm), or 160 meters of the same fiber at 850 nm.
        The model also assumes a receiver having a DFE as illustrated in Figure 6. It
is recognized that equivalent equalization can be accomplished at the transmitter
through the use of THP, DLP or other equalization techniques.

15   The rate equations used in modeling the laser are described in "On Approximate
Analytical Solutions of the Rate Equations for Studying Transient Spectra of Injection
Lasers", by D. Marcuse and T.P. Lee, IEEE Journal of Quantrum Electronics,
September 1983. The equations of the computer model are solved numerically using
a fourth order Runge-Kutta Algorithm. The bias current in the equations was set to

20 three times $I_{threshold}$. In addition, a 6dB extinction ratio is used.
        Figure 8 is a block diagram illustrating a channel model used in conjunction with
the rate equations. In Figure 8, a pseudo-random PAM-5 symbol generator 801
provides symbols to the laser model 803. The output of the laser model is then
provided to a multimode fiber model 805. The fiber model 805 is a linear system having

25 a Gaussian impulse response.
        Figure 9 is a graphic representing the impulse response of a linear system
having a Gaussian impulse response convolved with a single pole high pass filter with
corner frequency of 200 MHz. For the simulation, the fiber channel is modeled as in an
article "Equalization of Multimode Optical Fiber Systems," by B.L. Kaspers, Bell

30 Systems Technical Journal, September 1982. The Kaspers' model comprises a linear
dispersive system with a Gaussian impulse response given by equation 1. Such
Gaussian impulse response models are common throughout the literature and are
considered to be fairly accurate for fibers in which all modes are excited equally (i.e.
multimode fibers in an overfill launch condition).

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$$h(t) = \frac{1}{\sqrt{2\pi} \cdot \alpha T} \cdot e^{-[t^2/(2(\alpha T)^2)]}$$

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(Equation 1)

Where T is the period and α is a system dependent variable related to the bandwidth of the fiber. The corresponding frequency response of the channel is given by equation 2.

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$$H(f) = e^{-[(2\pi\alpha Tf)^2/2]}$$

(Equation 2)

The 3 dB bandwidth of the fiber is given by a equation 8 for a given baud period equal to 300 pico seconds.

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$$f_{3dB} = \frac{0.1325}{\alpha T}$$

(Equation 3)

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If the 3 dB bandwidth of the system is assumed to be one gigahertz, the value of $\propto$ is equal to 0.6625.

Figure 10 is a graph illustrating the output of a laser model based on the rate equations. The vertical axis 1001 represents the intensity of the laser.

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As can be seen from Figure 10, the signal appears to be somewhat noisy. The noise is partially accounted for by relaxation oscillation of the laser. Each time there is a sharp transition in the laser signal, overshoot and ringing results, as depicted in the graph of Figure 10.

Figure 11 is a magnified portion of the graph of Figure 10. Figure 11 is included
30 to illustrate the ringing present within the waveform of Figure 10.

Figure 12 is a graph of the waveform of Figure 10 after passage through the fiber channel model. In other words, Figure 12 is an illustration of the waveform presented to the receiver. As can be readily appreciated by observing Figures 10 and 12, the fiber channel performs significant filtering on the output of the laser. In other words, Figure

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12 is a convolution of the waveform in Figure 10 with the impulse response of the channel as illustrated in Figure 9.

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Figure 13 is an eye diagram of a simulated equalizer at the transition between a training mode and receiving PAM-5 symbols.

The simulated signal of Figure 12 is introduced to a receiver in Figure 13. The receiver used is one such as illustrated in Figure 6. The eye diagram depicted in Figure 13 is the output of the decision feedback equalizer 625 of Figure 6. The portion of the graph in Figure 13 delineated by 1301 represents a scatter diagram equivalent

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to the display 615(a) of Figure 6. The scatter diagram results after data has begun entering the receiver and being processed by the slicer but the equalizer has not yet been trained. In other words, the adaptive transversal filter has not yet adapted to the characteristics of the channel. A portion of the graph illustrated at 1303 in Figure 13 is an illustration of the equalizer being trained using two level symbols. At point 1315,

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within Figure 13, the five level Pam alphabet is transmitted to the receiver. The results of the receiving of the five level Pam -5 alphabet in the trained decision feedback equalizer 625 is the five levels 1305, 1307, 1309, 1311, and 1313 depicted in Figure 13.

Figure 14 is a graph of a magnified portion of the graph of Figure 13, illustrating the convergence of the equalizer during a training sequence.

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Figure 14 is a time expansion of the section 1301 of Figure 13. As can be seen from Figures 13 and 14, high data rates can be achieved using pulse amplitude modulation despite the presence of inner symbol interference, which may result from signaling faster than the Nyquist rate.

As can be seen from the models used to simulate the PAM-5 system transmitting

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data a faster than the Nyquist rate is viable using the techniques disclosed. Additionally using multilevel symbols has been shown to be viable and may be used to increase the data rate across fiber channels. The reduced noise tolerance of the system due to the reduced distance between signaling levels of a multilevel signaling system may be counteracted by the use of trellis coding the signals transmitted.

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Supplemental material with regard to the invention here and above described in Appendix A entitled "10Gb/s PMD Using PAM-5 Trellis Coded Modulation".

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